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Forensic age diagnostics by magnetic resonance imaging of the proximal humeral epiphysis

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Abstract

The most commonly used radiological method for age estimation of living individuals is X-ray. Computed tomography is not commonly used due to high radiation exposure, which raises ethical concerns. This problem can be solved with the use of magnetic resonance imaging (MRI), which avoids the use of ionizing radiation. The purpose of the present study was to evaluate the utility of MRI analysis of the proximal humeral epiphyses for forensic age estimations of living individuals. In this study, 395 left proximal humeral epiphyses (patient age 12–30 years) were evaluated with fast-spin-echo proton density–weighted image (FSE PD) sequences in a coronal oblique orientation on shoulder MRI images. A five-stage scoring system was used following the method of Dedouit et al. The intra- and interobserver reliabilities assessed using Cohen's kappa statistic were $\kappa = 0.818$ and $\kappa = 0.798$, respectively. According to this study, stage five first appeared at 20 and 21 years of age in males and females, respectively. These results are not directly comparable to any other published study due to the lack of MRI data on proximal humeral head development. These findings may provide valuable information for legally important age thresholds using shoulder MRI. The current study demonstrates that MRI of the proximal humerus can support forensic age estimation. Further research is needed to establish a standardized protocol that can be applied worldwide.

Keywords

Age estimation Proximal humeral epiphysis Magnetic resonance imaging

Abstract

The most commonly used radiological method for age estimation of living individuals is X-ray. Computed tomography is not commonly used due to high radiation exposure, which raises ethical concerns. This problem can be solved with the use of magnetic resonance imaging (MRI), which avoids the use of ionizing radiation. The purpose of the present study was to evaluate the utility of MRI analysis of the proximal humeral epiphyses for forensic age estimations of living individuals. In this study, 395 left proximal humeral epiphyses (patient age 12–30 years) were evaluated with fast-spin-echo proton density–weighted image (FSE PD) sequences in a coronal oblique orientation on shoulder MRI images. A five-stage scoring system was used following the method of Dedouit et al. The intra- and interobserver reliabilities assessed using Cohen's kappa statistic were $\kappa = 0.818$ and $\kappa = 0.798$, respectively. According to this study, stage five first appeared at 20 and 21 years of age in males and females, respectively. These results are not directly comparable to any other published study due to the lack of MRI data on proximal humeral head development. These findings may provide valuable information for legally important age thresholds using shoulder MRI. The current study demonstrates that MRI of the proximal humerus can support forensic age estimation. Further research is needed to establish a standardized protocol that can be applied worldwide.

Introduction

There is an important need for a forensic age estimation method for individuals who do not have birth records or who cannot present valid documentation of their date of birth [1, 2, 3]. In forensic science, age is used to determine the criminal responsibility of an individual and whether they should be charged as juveniles or adults [2, 3, 4]. Minimum age limits between 10 and 22 years have been established for criminal responsibility and other civil rights in different countries. The most frequently used critical age thresholds are 14, 16, 18, and 21 years [3, 4, 5]. In addition, recently, age estimation has played a critical role in procedures for refugees and asylum seekers as well as in marriage and adoption [3, 4, 6]. A United Nations High Commissioner for Refugees report showed that 866,000 asylum applications were filed worldwide in 2014, which represented a 45% increase compared with the previous period [7]. In the same report, 714,300 (45% increase) asylum applications were reported for all of Europe, including 570,800 for EU countries (47% increase) and 170,700 (95% increase) for southern Europe, and 134,600 (42% increase) were reported for North America. These data were compiled in the absence of birth registration and notification data because no reliable documentation regarding age was available for the individuals included in the reports. The number of applications for asylum in the UK during the second, third, and fourth quarters of 2014 and during the first and second quarters of 2015 totaled 31,333. Of these, 281 applications concerned age-disputed cases [8].

Currently, the age of living individuals is usually determined as recommended by the “Forensic Age Diagnostics of the German Society of Legal Medicine” via a combination of a physical examination, radiographic examinations of the left hand, a dental examination, and an orthopantomographic examination. If ossification of the hand is complete, radiological examination of the degree of clavicular ossification is recommended [2]. The Forensic Anthropology Society of Europe (FASE) subsection of the International Academy of Legal Medicine recommends that age estimation of living individuals should be performed using the following four tests: (a) physical assessment and the Tanner sexual classification test, (b) radiological evaluation of bone development using the Greulich and Pyle Atlas and the Tanner–Whitehouse method, (c) radiological evaluation of dental development using the Demirjian and Mincer methods, and (d) radiological assessment of clavicle sternal end fusion [3]. The primary area considered in skeletal radiological evaluations for age estimation in living individuals is epiphyseal fusion. Studies of epiphyseal closure have revealed minimal age limits for forensic age estimations using different scoring systems [1, 2, 3]. The most used radiological method for age estimation of living individuals is X-ray, whereas computed tomography (CT) is not commonly used due to high radiation exposure. Radiation exposure in the pediatric age group has recently raised ethical concerns [9, 10, 11]. Therefore, studies have been conducted on the use of ultrasonography of the distal radius [12], iliac crest [13], distal fibula [14], and medial clavicle epiphysis [15] and magnetic resonance imaging (MRI) of the medial clavicle epiphysis [16, 17, 18, 19], distal tibia and calcaneus [20, 21, 22], proximal tibial epiphysis [23, 24], iliac crest [25], hand and wrist [26, 27, 28, 29, 30, 31, 32, 33], and distal femur [24, 34, 35] to estimate age in different populations.

One of the least studied epiphyseal areas in the human skeleton is the proximal humeral epiphysis, and only a few studies have investigated the relationship between age and epiphyseal closure [36, 37, 38, 39, 40, 41, 42]. In past anatomical studies of the Lisbon, Coimbra, Bosnian, and McKern skeletal collections, the earliest fusion observed in proximal humeral epiphysis evaluations was reported to occur at an age of 17–19 years in males and 17 years in females [40, 41, 42, 43]. In previous X-ray analysis studies on living individuals in the USA, the youngest age at which fusion was reported to occur was 16 years in males and 14–16 years in females [38, 39].

MRI of the shoulder provides a significant advantage of achieving detailed imaging of the epiphyseal cartilage. Nonetheless, a literature survey revealed only two MRI studies on the proximal humeral epiphyseal fusion times. Kwong et al. [36] explored the development of the humeral head in a pediatric age group of 76 patients (32 girls and 44 boys) using MRI. According to the results, the growth plate remained open until 14 years of age, showing partial closure in the 14 to 16-year-old age group (19 cases) and complete closure by 17 years of age (8 cases). Although the results of the study by Kwong et al. [36] are encouraging in terms of developmental evaluation, several limitations are noted. The study was conducted in a small sample with an upper age limit of 17 years with limited information on the staging system used, and sex differences were not explored. The abovementioned limitations deem the method inappropriate for application in forensic age estimation of living individuals. Zember et al. [37] presented a review of the radiological developmental stages of the pediatric shoulder supported by case studies of different imaging methods. This study reported that the proximal humeral growth plate was initially smooth and transverse and progressively tented or tapered from 4 months of age. In addition, the proximal humeral growth plate began to close from approximately 14 years of age and fused at approximately 17 years of age. However, the small sample size and unequal age distribution were limitations of the study.

The limited studies on proximal humeral epiphyseal fusion motivated the present study because no MRI study on proximal humeral maturation for forensic age estimation has been performed to date. The aim of the present study was to evaluate the accuracy and utility of MRI analysis of the proximal humeral epiphyses for forensic age estimation of living individuals.

Materials and methods

This study is a retrospective, cross-sectional analysis of clinically acquired data that was conducted at the Bakirkoy Dr. Sadi Konuk Teaching and Research Hospital, Turkey. The study protocol was approved by the ethics committee of the hospital for the collection of MRI data of human subjects, and the study was conducted in accordance with the ethical standards of the Declaration of Helsinki (Finland).

Clinical data and MRI scans of patients admitted to the emergency service department and outpatient clinics of the hospital from January 2014 to March 2016 with diagnoses of shoulder pain and restricted active and passive shoulder joint movements were retrospectively evaluated. Patients with any pathology of the proximal humerus (e.g., tumor, fracture, infection, or surgical fixation) were excluded from the study. A total of 21 patients were excluded from the study due to surgical fixation (three patients), fracture (five patients), and insufficient age and sex information (13 patients). Finally, 395 patients (222 males and 173 females) aged 12–30 years were included in the study (Table 1).

Table 1. Ages of male and female subjects.

Age (years)	Male	Female
12	1	4
13	2	-
14	2	7
15	7	1
16	7	10
17	8	5
18	10	9
19	16	8
20	25	13
21	25	24
22	18	11
23	24	14
24	16	9
25	17	16
26	9	9
27	4	7
28	10	8
29	13	9
30	8	9
Total	222	173

All examinations were performed using a 1.5-T whole-body scanner (Avanto; Siemens, Erlangen, Germany); fast-spin-echo proton density–weighted images (FSE PD) of the shoulders were obtained in the coronal oblique orientation. The imaging parameters were as follows: TR of 500 ms, TE of 15 ms, FoV of 150 mm, voxel size of

$0.5 \times 0.5 \times 3.5\ mm^3$, and scan time of 1 min 44 s. An extremity coil (4-Channel Flex Coils, Siemens, Erlangen, Germany) was used.

The proximal humeral epiphysis was scored using the five-stage system of Dedouit et al. as follows [24]:

1. Step I:
A continuous horizontal cartilage layer thicker than 1.5 mm is apparent between the junctions of the metaphysis and the epiphysis, and the cartilage is multilaminar in appearance (Fig. 1). The multilaminar appearance is seen as a decreased signal intensity in the upper layer, an increased signal intensity in the middle layer, and a decreased signal intensity in the lower layer.

2. Step II:
A continuous horizontal linear cartilage signal intensity is present between the metaphysis and the epiphysis with a thickness greater than 1.5 mm and an increased signal intensity but without a multilaminar appearance (Fig. 2).

3. Step III:
A continuous horizontal linear cartilage signal intensity is present between the metaphysis and the epiphysis with a thickness less than 1.5 mm and an increased signal intensity (Fig. 3).

4. Step IV:
A discontinuous horizontal linear cartilage signal intensity is present between the metaphysis and the epiphysis with a thickness less than 1.5 mm and a discontinuous increased signal intensity (Fig. 4).

5. Step V:
No increased signal intensity is observed between the metaphysis and the epiphysis (Fig. 5).

In all cases, only the coronal series was used, and all MRI slices were evaluated.

Statistical analysis

Age data were expressed as the means or medians with standard deviations (SDs) or as lower and upper quartiles, minima, and maxima. Relationships between age and stage were evaluated via Spearman's correlation analysis. Between-sex comparisons were performed using the Mann–Whitney *U* test. A p value < 0.05 was considered significant. All MRI scans were evaluated by a radiologist (R1) twice to determine intraobserver reliability and by a second radiologist (R2) to assess interobserver error. R1 and R2 were blinded to the demographic data of the participants. The two radiologists had 20 and 5 years of experience with musculoskeletal imaging, respectively. R1 was experienced in age estimation methods using CT and MRI, whereas the experience of R2 was limited. Cohen's kappa nonparametric test (κ) was used to evaluate the intra- and interobserver variabilities. The Altman [44] system was used to interpret the κ values as follows: $\kappa < 0.20$, poor agreement; $\kappa = 0.21–0.40$, fair agreement; $\kappa = 0.41–0.60$, moderate agreement; $\kappa = 0.61–0.80$, good agreement; and $\kappa = 0.81–1.00$, very good agreement.

Results

The mean ages of the male and female subjects were 22.63 ± 4.04 years and 22.67 ± 4.5 years, respectively. A significant difference between the sexes was observed for stages 2 ($p = 0.022$), 3 ($p = 0.041$), and 5 ($p = 0.004$). Spearman's rank correlation analysis revealed a significant positive relationship between age and the ossification stage of the proximal humeral epiphysis (all subjects: rho = 0.638, $p < 0.001$; males: rho = 0.472, $p < 0.001$; females: rho = 0.790, $p < 0.001$). The intraobserver reliability for the proximal humeral epiphysis was κ = 0.818, and the interobserver reliability was κ = 0.798, indicating very good and good reliability, respectively.

In female patients, the earliest appearances of stages 4 and 5 were 16.2 and 21.3 years, respectively. In male patients, the earliest appearances of stages 4 and 5 were 16.3 and 20.6 years, respectively. Table 2 shows the minimum and maximum ages, the means ± SDs, and the lower and upper quartiles of all parameters.

Table 2. Minimum and maximum ages, with means ± SDs, lower and upper quartiles and medians, at all stages of proximal humeral epiphysis.

Stage	Sex	*n*	Mean ± SD	Min–max	LQ, UQ, median
1	Female	3	12.86 ± 1.06	12.2–14.1	12.20, –, 12.30
	Male	5	14.14 ± 1.40	12.4–15.7	12.75, 15.50, 14.20
2	Female	7	14.01 ± 1.05	12.4–15.2	12.70, 14.80, 14.30
	Male	6	15.63 ± 1.38	13.3–17.2	14.72, 16.82, 15.70
3	Female	37	19.19 ± 2.20	14.6–22.7	17.15, 21.25, 19.70
	Male	18	17.88 ± 2.33	14.3–21.4	16.10, 20.30, 17.20
4	Female	77	22.56 ± 2.98	16.2–29.2	20.80, 24.35, 22.70
	Male	166	23.31 ± 3.36	16.3–30.4	20.70, 25.30, 23.20
5	Female	49	27.30 ± 2.54	21.3–30.7	25.45, 29.60, 27.70
	Male	27	24.80 ± 3.70	20.6–30.6	21.20, 28.30, 23.90

Discussion

Our study examined a large sample ($N = 395$) of clinically acquired data with similar sex distributions allowing us to obtain a minimum age for each stage. Table 3 lists the minimum ages at which closure of the proximal humeral epiphyses was first noted in both our study and prior studies. Notably, the age distribution of our sample was not homogenous. The unequal age distribution was a result of the availability of clinical images, which as in any retrospective study, can potentially affect the age thresholds. This issue should be addressed in future MRI studies with a prospective design.

Comparing the data obtained in our study with the results of previous studies was difficult because few studies have been conducted on the subject, and different methods and populations have been used. However, the current study has some differences compared with previous studies that need to be highlighted. First, direct inspection studies of skeletal collections may be limited in their assessment of epiphyseal developmental details. Likewise, X-ray offers a more limited image analysis than MRI. In epiphyseal field evaluations, the information provided by MRI for bone and cartilaginous tissue is more detailed than the single-plane bone assessments obtained by X-ray. In terms of the data that can be obtained from staging and radiological techniques, comparisons of data obtained from anatomic and X-ray studies with data from MRI studies are not appropriate. This issue is evident in the study by Fan et al. [46], in which the same patient's X-ray and MRI examinations were evaluated with the same staging system. The abovementioned study [46] demonstrated that the minimal age limits for a given stage determined by X-ray were lower than those determined by MRI.

In our study, MRI was applied in the coronal plane, and the entire sequence of slices was considered by observers. Assessment of ossification of the epiphyseal plate at different planes may be important for epiphyseal ossification evaluation. In his forensic age estimation study of the knee with MRI, Dedouit evaluated [24] sagittal sections for distinctions between stages 2–3 and 3–4, in addition to coronal sections, although this analysis had minimal effects on the results. Conversely, Scharte et al. [47] reported a 35.6% difference between the axial and coronal planes in clavicular CT. In an MRI study, De Tobel et al. [48] used three different planes for third molar mineralization, and consequently, MR images in the sagittal plane proved to be essential for staging. In our study, only coronal oblique sections were used. As a result, the provided age intervals obtained as a result of our study only apply to coronal MRI of the proximal humerus. Additional studies are needed to determine the effect of different planes on age estimation.

In future studies, the use of T1-weighted MRI and different planes could be employed for evaluating proximal humeral epiphyses. The results should be evaluated and compared with the findings of this and other studies to lay the foundation for a solid methodology for estimating age using shoulder joint MRI.

Although our results were obtained from a relatively limited geographical population that lacked socioeconomic status data, these findings are important in that they present results of the proximal humeral epiphysis in a contemporary population. In particular, the growth rates within a population are mainly related to the socioeconomic status of that population and are independent of ethnicity [49, 50]. A low socioeconomic status is related to growth retardation and can affect age estimates [49, 50]. According to current human development index data [51], the Turkish population falls in the category of low socioeconomic status. Some differences in minimal age limits reported in previous studies of the Turkish population include medial clavicle ossification and the proximal femoral and distal tibial epiphyses [22, 52, 53, 54]. Consequently, a low socioeconomic status should be taken into consideration when evaluating the results of the current study.

In general, females reach higher stages of ossification at a younger age than males. In our sample, this phenomenon was true for stages 1 and 2, although the ossification of males surpassed that of females from stages 3 and 5. However, this finding may be due to sample bias and needs to be verified in future research.

According to the results of this study, the minimal age determined for each stage seems to be useful for applications in determining legal age limits. Furthermore, MRI offers superior depiction of the bone and cartilage, while it does not require ionizing radiation and is not user dependent.

Table 3. Comparative table of studies on the closure of the proximal humeral epiphysis.

	Study sample				**Study protocol**	**Minimum closure age**	**Reference**
	Population	**Male**	**Femal e**	**Age range**			
1	USA-Living individuals	44	32	3months - 17 years	MRI: staging undefined	17 yeas (sex differences not defined	[35]
2	USA-study population not defined	?	?	?	MRI, X-ray: staging undefined	17 yeas (sex differences not defined	[36]
3	USA-Living individuals	258	179	10-21 years	X-ray staging: 4 stages	Female:20 years Male:21years	[37]
4	Indian-Living individuals	0	80	13-21 yeas	X-ray staging: 3 stages	Female: 18 years	[38]
5	Lisbon skeletal collection	65	56	9-29 years	Direct analysis. Staging: 3 stages	Female 17 years, Male: 17 years	[39]

6	Bosnian skeletal collection	232	0	14-30 years	Direct analysis. Staging: 5 stages	Male: 18 years	[40]
7	Bosnian skeletal collection	114	0	17-30 years	Direct analysis. Staging: 4 stages	Male:18 years	[41]
8	Mckern skeletal collection	325	0			Male: 17 years	
9	Living individuals	222	173	12-30 years	MRI Staging: Schmerling 4 stages + Kellinghaus substages	Male: 18.6 years Female:17.2 years	Present study

Conclusion

Dedouit's five-stage system and fast-spin-echo proton density–weighted images (FSE PD) of the proximal humeral epiphysis can provide important information regarding age. Our data show that these techniques may be useful as a supportive method for estimating the ages of living subjects who are adolescents and young adults.

Notes

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflicts of interest.

Research involving human participants and/or animals

This article does not contain any studies with animals performed by any of the authors.

Informed consent

For this type of study, formal consent was not required.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards

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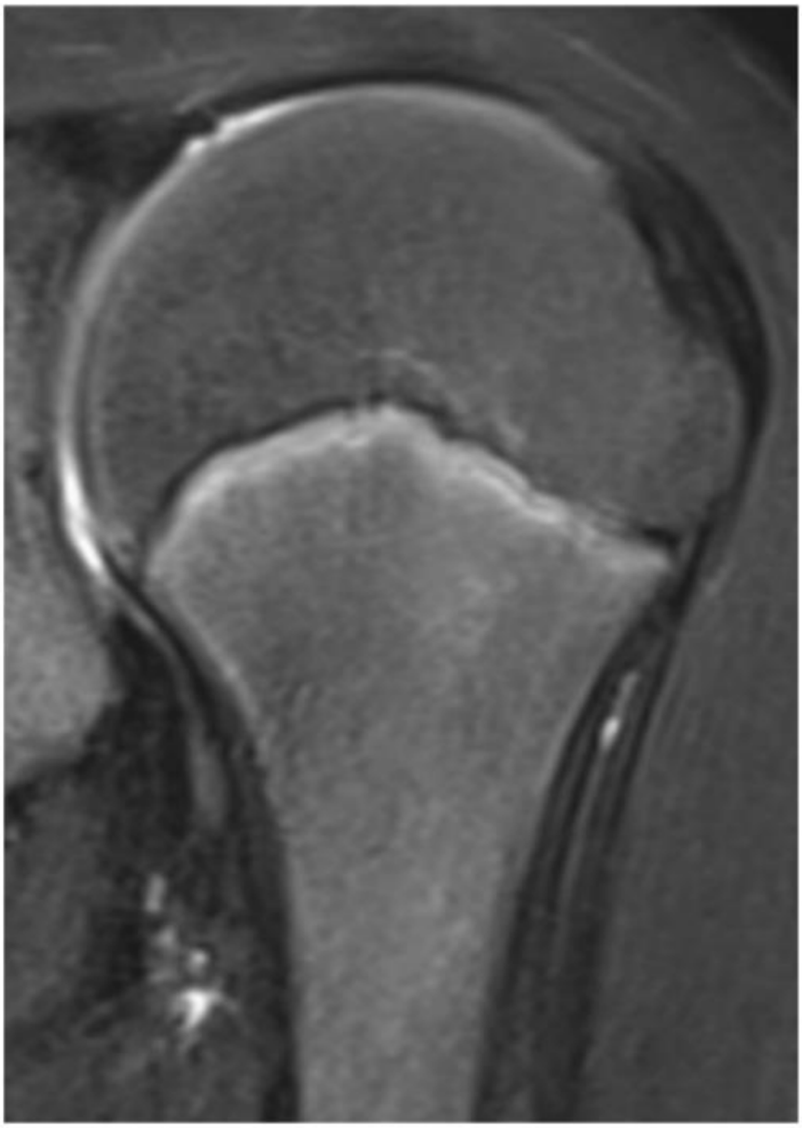

Fig. 1 Fast-spin-echo proton density–weighted (FSE PD) sequences in coronal oblique orientation on shoulder MRI images: Stage 1 for proximal humeral epiphysis

Fig. 2 Fast-spin-echo proton density–weighted (FSE PD) sequences in coronal oblique orientation on shoulder MRI images: Stage 2 for proximal humeral epiphysis

Fig. 3 Fast-spin-echo proton density–weighted (FSE PD) sequences in coronal oblique orientation on shoulder MRI images: Stage 3 for proximal humeral epiphysis

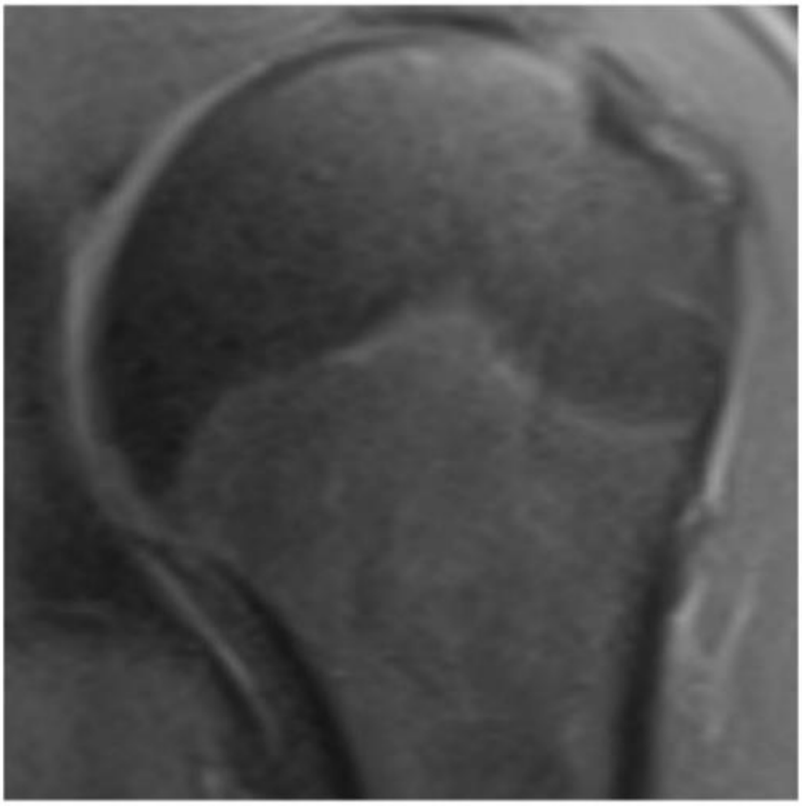

Fig. 4 Fast-spin-echo proton density–weighted (FSE PD) sequences in coronal oblique orientation on shoulder MRI images: Stage 4 for proximal humeral epiphysis

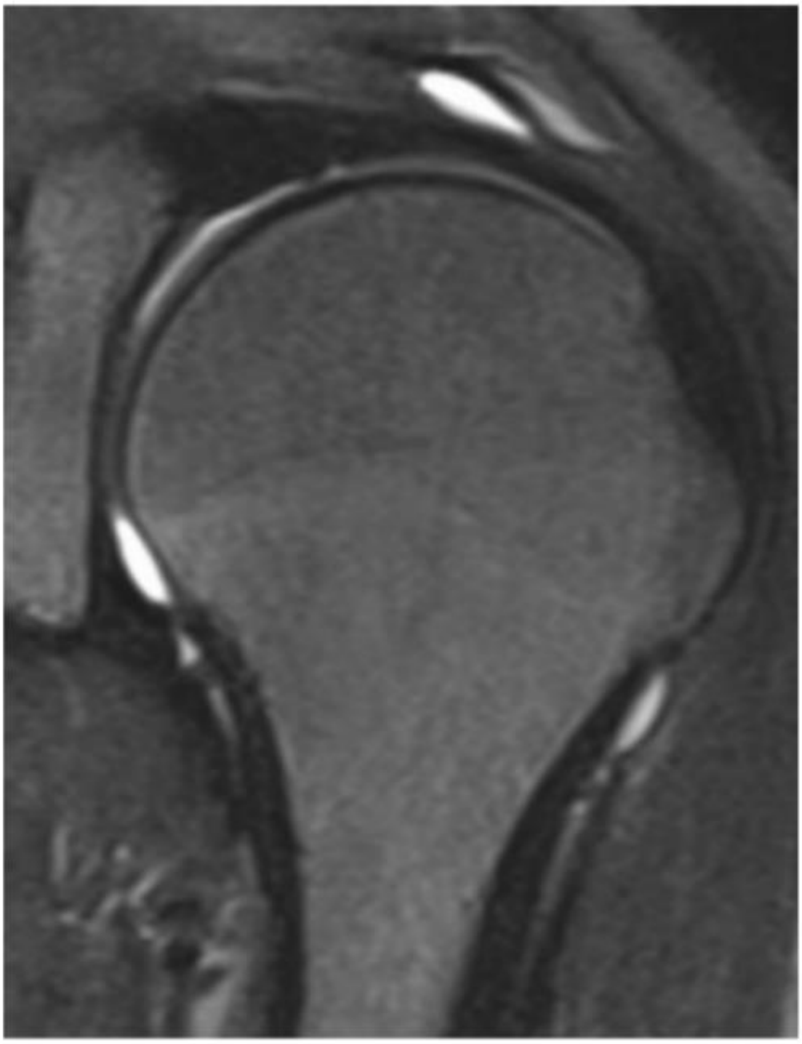

Fig. 5 Fast-spin-echo proton density–weighted (FSE PD) sequences in coronal oblique orientation on shoulder MRI images: Stage 5 for proximal humeral epiphysis